Renewable and Sustainable Energy Reviews 16 (2012) 1817–1827

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Numerical simulation and optimal design for composite high-pressure hydrogen storage vessel: A review

P.F. Liu[a], J.K. Chu[a], S.J. Hou[a], P. Xu[b], J.Y. Zheng[a,*]

[a] *Institute of Chemical Machinery and Process Equipment, Zhejiang University, Hangzhou 310027, Zhejiang Province, China*
[b] *Institute of Applied Mechanics, Zhejiang University, Hangzhou 310027, Zhejiang Province, China*

ARTICLE INFO

Article history:
Received 29 June 2011
Received in revised form
21 December 2011
Accepted 2 January 2012
Available online 18 February 2012

ABSTRACT

Composite high-pressure hydrogen storage vessel has been increasingly applied to the hydrogen fuel cell car. The design of a composite vessel involves various integrated parameters such as the progressive failure properties, the burst pressure and fatigue lifetime. The favorable combination of high reliability and practicability of the composite vessel is a challenging task from the beginning of design. This paper gives a comprehensive review on recent development of numerical simulation and optimization for the designed composite vessel. First, methods on damage modeling for predicting the failure properties and degradation mechanisms of the composite vessel are reviewed. Second, research on predicting the burst pressure and lifetime of the composite vessel is reviewed. The academic work on the damage modeling, progressive failure analysis and finite element implementation which explains the failure properties and stiffness degradation mechanisms of the composite vessel is summarized. Computational methods on the burst pressure, the strength reliability and lifetime of the composite vessel are also evaluated. Finally, ideal design which aims to lessen the weight of a composite vessel to the maximum extent under strength and stiffness constraints is commented. The optimization efficiency using different algorithms is also comparatively studied. The numerical simulation and optimization as important fundamental research constitute a design platform for the composite vessel. It deserves pointing out the lightweight design conception as a remarkable tendency that combines advanced numerical methods and manufacturing technique develops rapidly, commits to improving the reliability and practicability of the composite vessel. It is expected the lightweight design technique plays an increasingly important role in developing the composite vessel as their value is further highlighted.

Contents

* Corresponding author. Tel.: +86 571 87953370; fax: +86 571 87953393.
E-mail address: jyzh@zju.edu.cn (J.Y. Zheng).

1364-0321/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2012.01.006

1. Introduction

The energy crisis and environment pollution all around the world enable it necessary to explore advanced energy. Hydrogen energy is commonly considered as important renewable and sustainable energy in the new century because of a series of advantages such as cleanness, high-efficiency and fruitful source [1–4]. Hydrogen can be generated by solar energy, wind energy, biomass and water [5–7]. Yet, the use of hydrogen energy deals with many technique problems such as the hydrogen generation, the hydrogen storage and transport, and the hydrogen combustion. To promote the hydrogen energy industry and potential hydrogen economy, it is critical to develop hydrogen energy technique [8–10].

The hydrogen fuel cell car is typically representative of developing hydrogen industry. Safe, high-efficiency and economical hydrogen storage technique is a key to ensure favorable run of hydrogen energy car. Among many hydrogen storage patterns including high-pressure gaseous storage, cryogenic liquid storage and chemical hydrogen storage, high-pressure gaseous storage has become the most popular technique [11–14]. For example, the hydrogen fuel cell cars used in both 2008 Beijing Olympic Games and 2010 Shanghai World Exposition used composite high-pressure storage vessel.

Because of the limited space available for the car, the basic design requirements for the storage vessel are safety, reliability and economy. However, the composite pressure vessel may work under the high-pressure and high-temperature environment. This not only presents a strong challenge to the physical and mechanical performance, but also to the reliable and economical design about how to achieve a perfect combination of safety performance and low cost [15]. Conventional movable metal pressure vessel can no longer be competent for the rigorous need of high strength – and stiffness – weight ratios. In this case, the composite filament wound technology is introduced to improve the storage efficiency [16–18]. To reach the aim of large-capacity hydrogen storage, the composite vessel includes an inner aluminum layer and se outer carbon fiber/epoxy composite wound layers in China [19]. In general, the composites are used to make the pressure vessel by placing them in different orientations for different layers and in a common orientation within a layer. These layers are stacked in such a way to achieve high stiffness and strength [20]. The designable properties of the composite vessel enable it flexibly applicable to different working conditions and environments by adapting the fiber wound patterns, the dome shapes and the layer thickness.

The design of the composite vessel as a fundamental research work relates the physical and mechanical properties of materials to the geometry. Essentially, two main works are required for the design: one is the prediction of burst pressure and another is the optimization. The burst pressure denotes the limit load-carrying ability of the composite vessel. Since the failure mechanisms of composites are complicated from the view of composite micromechanics, including the matrix cracking, fiber/matrix debonding and fiber breakage as well as their interactions [21,22], accurate prediction of the burst pressure is a challenging work. Besides, proper explanation of the stiffness degradation as the physical response to the continuous failure also needs special theory.

With the development of computer, the finite element analysis has become a powerful tool to deal with the numerical problems of complex structures [23]. By combining the continuum damage mechanics (CDM) and the finite element analysis (FEA), the progressive failure analysis of the composite vessel is used to account for the stiffness degradation and to predict the burst pressure [24,25]. Especially, the FE technique that implements the damage model arouses wide academic attention.

In terms of the optimization of composite vessel, several intelligent algorithms that simulate the evolutionary principles in the disciplines of computational biology, physics and immunology, have been used. The popular algorithms are the genetic algorithm, simulated annealing and artificial immune system [26–28]. The optimization attempts to improve the weight, strength, reliability and lifetime of the composite vessel by designing the wound angles and thickness.

As the design method and manufacturing technique advance, the composite vessel takes on the approach to the lightweight development. The weight decrease has become a technique bottleneck which restricts the economy and practicability of the composite vessel. In this case, it is urgent that a set of material-structure-processing integrated design and calculation method of the composite vessel be established. It is true there are some other manufacturing and test reasons affecting the performance of composite vessel, so what a large role the design plays may require evaluated. However, the importance of numerical simulation and optimization is expected to be further highlighted by the present review.

2. Geometry structure of composite hydrogen storage vessel

Fig. 1 shows a composite vessel used in the hydrogen fuel car. Fig. 2 shows the basic structure and wound pattern of composite vessel. The vessel includes an inner aluminum layer and several outer composite layers. The aluminum layer prevents the gas leakage and provides a mould for filament wound, and the composite layers are responsible for resisting the internal pressure. For the cylinder part, spiral wound and hoop wound patterns are used. Yet, only spiral wound pattern appears at the head part.

From the manufacturing principle, the wound trace for composite layers is a combination of the rotation of aluminium liner and the axial movement of wound machine. The spiral wound angle α_0 at the cylinder is determined by [29]

$$\alpha_0 = \arcsin\left(\frac{r}{R_0}\right) \tag{1}$$



Fig. 1. Lightweight composite high-pressure hydrogen storage vessel used in the hydrogen fuel-cell vehicle.

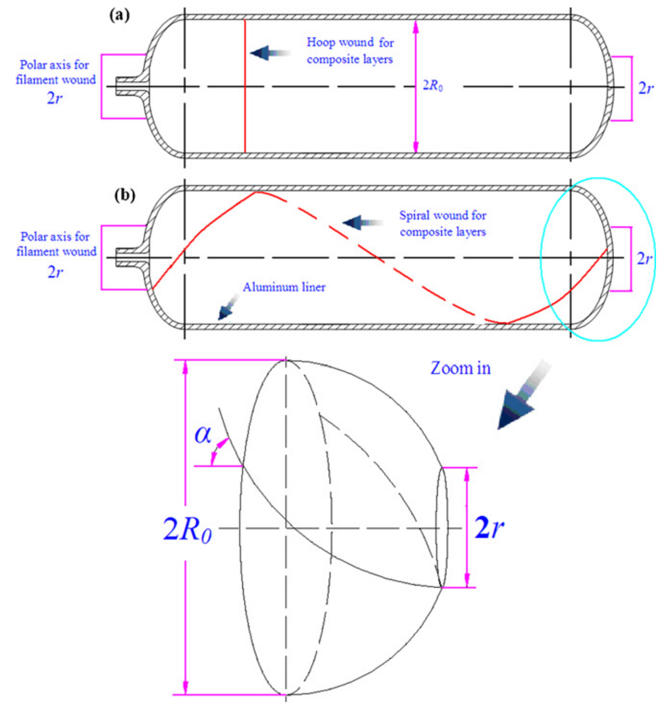


Fig. 2. Basic structure and wound pattern of composite vessel: (a) hoop wound and (b) sprial wound.

where r is the radius of the polar axis and R_0 denotes the inner radius of the cylinder.

The spiral wound at the head obeys the geodesic path algorithm, marking the shortest distance between any two points on the head. The spiral wound angle α at the head changes from 90° at the polar axis to α_0 at the cylinder [29]

$$\alpha = \arcsin\left(\frac{r}{R}\right) \tag{2}$$

The thickness H of the composite layer at any radius R of the head is calculated by [29]

$$H = h\sqrt{\frac{(R_0^2 - r^2)}{(R^2 - r^2)}} \tag{3}$$

where h is the wound thickness at the cylinder. From Eqs. (1)–(3), the polar radius r affects the wound angle α and the thickness H at the head.

3. Finite element modeling of composite hydrogen storage vessel

Accurate and fast modeling of the composite vessel is an important work in the design, which involves many parameters such as the wound angle and thickness. Parametric modeling by exacting these parameters as the design variables facilitates the strength prediction and optimization for the composite vessels with different sizes.

3.1. Design theories

In general, the composite vessel is considered as the composite laminated structure. Now, there are two main design theories: grid theory and composite laminate theory.

3.1.1. Grid theory

The basic assumptions according to the grid theory are: (1) only the longitudinal carbon fiber bears the pressure and (2) effects of wound patterns are neglected. The grid theory can be used to calculate the thickness of each composite layer and the longitudinal in situ fiber strength. The strength value is inversely solved by the burst pressure of composite vessel. Chen [30] gave a set of design method of the composite vessel based on the grid theory, and the total composite wound thickness h_f is expressed as

$$\begin{cases} h_{f\alpha} = \dfrac{R_0 P_b}{2\sigma_{fb}\cos^2\alpha_0}, \qquad h_{f\theta} = \dfrac{R_0 P_b}{2\sigma_{fb}}(2 - \tan^2\alpha_0) \\ h_f = h_{f\alpha} + h_{f\theta} = \dfrac{3R_0 P_b}{2\sigma_{fb}} \end{cases} \tag{4}$$

where $h_{f\alpha}$ and $h_{f\theta}$ are longitudinal and hoop wound thickness, P_b is the burst pressure of composite vessel, and σ_{fb} is the in situ strength of carbon fiber.

It should be pointed out the grid theory is merely an ideal design method which largely depends on the processing parameters and the sizes of the experimental composite vessel. This shows seeking a more efficient design theory is necessary.

3.1.2. Composite laminate theory

The basic assumptions of the classical composite laminate theory (CCLT) are: (1) perfect bonding appears at the interface between each layer, (2) the mechanical properties of composite laminates are substituted by those of a middle plane, and (3) the normal stress is neglected at the section parallel to the middle plane. Lifshitz et al. [31] proposed a method using the CCLT to calculate the stress and strain in non-symmetric wound pressure vessel with thick metal liners. However, the last two assumptions above do not strictly hold for 3D composite vessel. In this case, Parnas et al. [32] derived the elastic stress and displacement solutions for 3D cylindrical composite laminates based on the CCLT and generalized plane strain assumption. As the liner is assumed isotropic and the composite layers are considered transversely isotropic, Chapelle et al. [33] further derived the analytical solutions of the stress, strain and displacement for 3D cylindrical composite laminates.

Fig. 3(a) shows the cylindrical part of composite vessel and Fig. 3(b) describes a representative volume element taken from

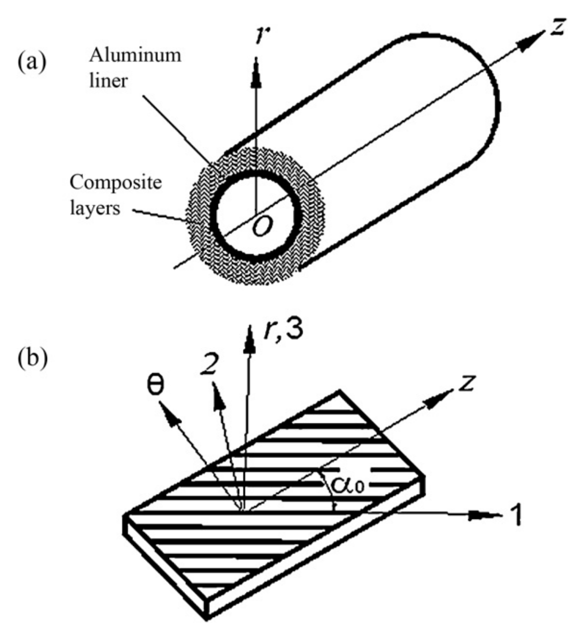


Fig. 3. (a) Composite hydrogen storage vessel (transverse section) and (b) schematic illustration of the relationship between the on-axis coordinate (1,2,3) and the off-axis coordinate (r,θ,z).

Fig. 3(a), showing the principal direction (1,2,3) of a composite layer under the cylindrical coordinate (r,θ,z). If the axial strains at all layers are assumed constant and the shear strains are independent of z, the strain–displacement relationship is given by [33]

$$\varepsilon_r^{(k)} = \frac{du_r^{(k)}}{dr}, \quad \varepsilon_\theta^{(k)} = \frac{u_r^{(k)}}{r}, \quad \varepsilon_z^{(k)} = \frac{du_z^{(k)}}{dz} = \varepsilon_0, \quad \gamma_{z\theta}^{(k)} = \frac{du_\theta^{(k)}}{dz} = \gamma_0 r \tag{5}$$

where ε_z is the axial strain, $\gamma_{z\theta}$ is the shear strain and γ_0 is twist per unit length.

The off-axis stress-strain relationship under the hygro-thermo-mechanics multiphysics field is expressed as

$$\begin{bmatrix} \sigma_z \\ \sigma_\theta \\ \sigma_r \\ \tau_{z\theta} \end{bmatrix}^{(k)} = \begin{bmatrix} \bar{C}_{11} & \bar{C}_{12} & \bar{C}_{13} & \bar{C}_{16} \\ \bar{C}_{21} & \bar{C}_{22} & \bar{C}_{23} & \bar{C}_{26} \\ \bar{C}_{13} & \bar{C}_{23} & \bar{C}_{33} & \bar{C}_{36} \\ \bar{C}_{16} & \bar{C}_{26} & \bar{C}_{36} & \bar{C}_{66} \end{bmatrix}^{(k)} \begin{bmatrix} \varepsilon_z \\ \varepsilon_\theta \\ \varepsilon_r \\ \gamma_{z\theta} \end{bmatrix}^{(k)} - \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_6 \end{bmatrix}^{(k)} \Delta T - \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_6 \end{bmatrix}^{(k)} \Delta C \tag{6}$$

where the symbols $\bar{C}_{ij}(i, j = 1, 2, 3, 6)$ are off-axis elastic constants of composites. The symbols $\sigma_z, \sigma_\theta, \sigma_r$ and $\tau_{z\theta}$ are the off-axis axial, hoop, radial and shear stresses, respectively. $\varepsilon_z, \varepsilon_\theta, \varepsilon_r$ and $\gamma_{z\theta}$ are the corresponding strains, respectively. ΔT and ΔC are temperature and moisture concentrations, respectively. $\alpha_i(i = 1, 2, 3, 6)$ and $\beta_i(i = 1, 2, 3, 6)$ are the corresponding thermal and moisture expansion coefficients.

For the kth layer, the equilibrium equation under the cylindrical coordinate is given by [33]

$$\frac{1}{r}\frac{\partial(r\sigma_r^{(k)})}{\partial r} - \frac{\sigma_\theta^{(k)}}{r} = 0 \tag{7}$$

After introducing the displacement continuity conditions, the radial stress continuity conditions as well as the axial equilibrium and zero torsion conditions between two neighbouring layers, the analytical solutions for the strain, stress and displacement can be derived by Eqs. (5)–(7).

3.2. Finite element modeling

The finite element analysis and CCLT are combined to constitute the design platform since the analytical solutions cannot be competent for progressive failure analysis. Yan et al. [34] discussed the finite element technique of the composite vessel including finite element modeling and commercial finite element codes. Besides, the reliability, efficiency and cost as well as the further prospect are discussed. Liu and Zheng [35,36] established parametric finite element model for the cylinder part using ANSYS finite element code. Wang et al. [37] established the finite element model of the composite vessel with variable thickness and angles at the head. Li et al. [38] established the design model of the composite vessel using ANSYS-APDL (Ansys Parametric Design Language) and VC++ language. However, the design platform has not been completely established since ANSYS software does not provide an efficient modeling module for composites until now. Based on the composite micromechanics and modified CCLT, Antunes et al. [39] established the finite element model of the composite vessel using ABAQUS and Algor finite element codes. Park et al. [40] calculated the filament wound patterns using semi-geodesic path equations for an arbitrary surface, and established the finite element model of the composite vessel using ABAQUS finite element code. Further, Kim et al. [41] used the semi-geodesic path algorithm to calculate possible wound patterns by considering the windability and slippage between the fiber and the mandrel surface. Yet, these work concentrates on the specific composite vessel and does not perform parametric modeling. Recently, we established the parametric finite element model by combining the ANSYS and ABAQUS finite element codes. Fig. 4 shows the flow chart of finite element modeling of composite vessel, and Fig. 5 shows a 90° mesh model. A subroutine is written using ANSYS-APDL to establish the geometry and mesh model, where some characteristic parameters such as the composite lay-up thickness, the cylinder inner radius and thickness, the liner thickness as well as the mouse radius and thickness are extracted as the design variables. Then, the mesh model is imported into ABAQUS by the ANSYS/ABAQUS file transformation interface. After that, a local cylindrical coordinate system (r,θ,z) is defined in ABAQUS and the composite lay-up module is employed to assign the lay-up angles and material properties for composite elements. Fig. 6 shows schematic stress distributions under working pressure for a composite vessel. The wound angles at the cylinder are 90°, −90°, α_0, $-\alpha_0$, 90°, −90°, α_0, $-\alpha_0$, 90° and −90° in turn. It can be seen that the maximum principal stress appears at the joint of the head and cylinder

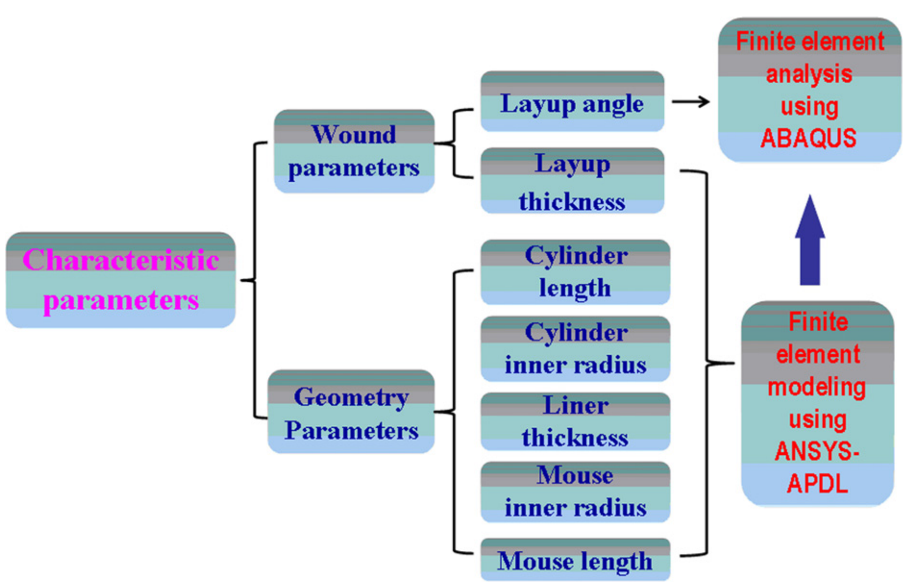


Fig. 4. Flow chart of finite element modeling of composite vessel.

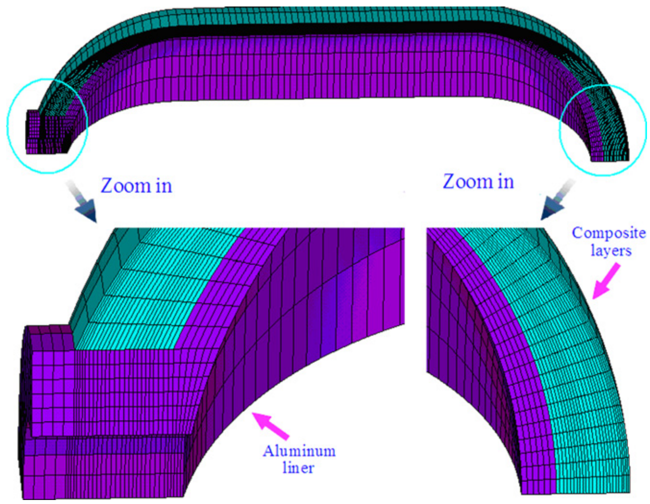


Fig. 5. Parametric finite element model of composite vessel.

for the spiral wound layer, in good agreement with Yang's results [29].

4. Failure analysis and strength prediction of composite hydrogen storage vessel

Currently, finite element technique has been widely used to predict the failure properties and strengths of composites. In the following, some recent research on the failure analysis and strength prediction of the composite vessel is reviewed.

4.1. Damage constitutive modeling

With the accelerating application to the hydrogen fuel cell car in China, the composite vessel may be subjected to the hygro-thermo-mechanics environment arising from the subtropical climate. The aging of epoxy matrix leads to the stiffness and strength degradation, thereby affecting the lifetime of composite vessel. In this case, it is significant to explore the failure properties using progressive failure analysis.

Strictly speaking, there are two distinct failure mechanisms for the composite vessel: intralaminar damage and interlaminar delamination. From the burst experiments of composite vessels, the intralaminar damage instead of interlaminar delamination affects the mechanical performance of the composite vessel. This is because two neighbouring composite layers still keep normally pressing and tangentially slipping despite a little interlaminar failure appearing before the burst [42]. Thus, only the intralaminar failure is generally considered.

Since Kachanov [43] proposed the CDM to study the creep rupture of metals, progressive failure analysis using the CDM has been widely used to predict the stiffness degradation and damage evolution properties of composites by defining phenomenological damage tensors and damage evolution laws [44–50]. A schematic 3D damage model from Eq. (6) under the hygro-thermo-mechanics field is expressed as

$$\begin{bmatrix}\sigma_z\\ \sigma_\theta\\ \sigma_r\\ \tau_{z\theta}\end{bmatrix}^{(k)} = C_d \begin{bmatrix}\varepsilon_z-\alpha_1\,\Delta T-\beta_1\,\Delta C\\ \varepsilon_\theta-\alpha_2\Delta T-\beta_2\,\Delta C\\ \varepsilon_r-\alpha_3\Delta T-\beta_3\,\Delta C\\ \gamma_{z\theta}-\alpha_6\Delta T-\beta_6\,\Delta C\end{bmatrix}^{(k)},\quad C_d=\begin{bmatrix}(1-d_f)\bar{C}_{11} & (1-d_f)(1-d_m)\bar{C}_{12} & (1-d_f)\bar{C}_{13} & \bar{C}_{16}\\ (1-d_f)(1-d_m)\bar{C}_{21} & (1-d_m)\bar{C}_{22} & \bar{C}_{23} & \bar{C}_{26}\\ (1-d_f)\bar{C}_{13} & \bar{C}_{23} & \bar{C}_{33} & \bar{C}_{36}\\ \bar{C}_{16} & \bar{C}_{26} & \bar{C}_{36} & (1-d_s)d_s\bar{C}_{66}\end{bmatrix}^{(k)} \quad (8)$$

where $d_i(i=f, m, s)$ are the damage variables representing the fiber breakage, matrix cracking and fiber/matrix interface failure, respectively.

According to Lemaitre and Chaboche [51,52], Ristinmaa and Ottosen [53], Schapery [54], Murakami and Kamiya [55], Hayakawa et al. [56] and Simo et al. [57], the damage constitutive modeling based on the CDM is summarized. For the damaged materials, the Cauchy stress tensor σ can be substituted by the nominal stress tensor $\bar{\sigma}$

$$\sigma=(1-D)\bar{\sigma} \quad (9)$$

where $0\le D\le 1$. $D=0$ represents the perfect materials and $D=1$ denotes the completely damaged materials.

The Helmholtz free energy per unit mass ψ for elastic materials under isothermal conditions is written as

$$\rho\psi=\rho\psi^e(\varepsilon_{ij}-\varepsilon_{ij}^p, D_{ij})+\rho\psi^d(\kappa) \quad (10)$$

where ψ^e and ψ^d are the free energy which represents the elastic deformations and damage hardening, respectively. κ is an internal variable and ρ is the density.

The thermodynamic conjugate forces (Y_{ij}, B) corresponding to the internal variables (D_{ij}, κ) are expressed as

$$\sigma_{ij}=\rho\frac{\partial\psi}{\partial\varepsilon_{ij}},\qquad Y_{ij}=-\rho\frac{\partial\psi}{\partial D_{ij}},\qquad B=\rho\frac{\partial\psi}{\partial\kappa} \quad (11)$$

The Clausius–Duhem dissipation inequality according to the CDM is written as

$$\gamma=-\rho\dot{\psi}+\sigma_{ij}\dot{\varepsilon}_{ij}\ge 0 \quad (12)$$

where γ is the power of dissipation due to damage. If the dissipation γ reaches the maximum, the damage evolution law is given by

$$\dot{D}_{ij}=\dot{\lambda}^d\frac{\partial F^d}{\partial Y_{ij}},\qquad \dot{\kappa}=-\dot{\lambda}^d\frac{\partial F^d}{\partial B} \quad (13)$$

After introducing three damage potential functions $F^d(Y_{ij}, D, B)$ for three intralaminar failure mechanisms for composites, the consistency parameter λ^d, the damage variable D and elastic matrix C_d are obtained as the functions of stress and strain.

4.2. Failure criteria for composites

Failure shows the degradated ability to resist the external load. The failure properties of a composite vessel depend on the geometry sizes, the material features, the loading history and environment. Over the past five decades, the popular failure criteria are the maximum stress, Hashin, Hoffman, Hinton, Christensen, Rotem, McCartney, Yamada-Sun, Chang-Chang, Tsai-Hill, Tsai-Wu, Puck and Huang's criteria [58–70]. In terms of the tensor notation, the generalized Tsai-Wu criterion is written as

$$F_i\sigma_i+F_{ij}\sigma_i\sigma_j+F_{ijk}\sigma_i\sigma_j\sigma_k\ge 1,\quad i,j,k=1,2,\ldots,6 \quad (14)$$

where F is strength coefficient tensor.

Such as the Tsai-Wu, Tsai-Hill and Hoffman failure criteria identify the failure of composites, but they cannot identify the failure modes. In contrast, the maximum stress, Hashin, Christensen, Rotem, McCartney, Yamada-Sun, Hinton, Chang-Chang, Puck and Huang criteria can identify the failure modes by defining the failure criteria for the tensile and compressive failure as well as the fiber breakage, matrix cracking and delamination.

Hinton et al. [60] explored existing failure theories for composites by launching a world-wide failure exercise, and tested some leading failure theories by comparing experimental data.

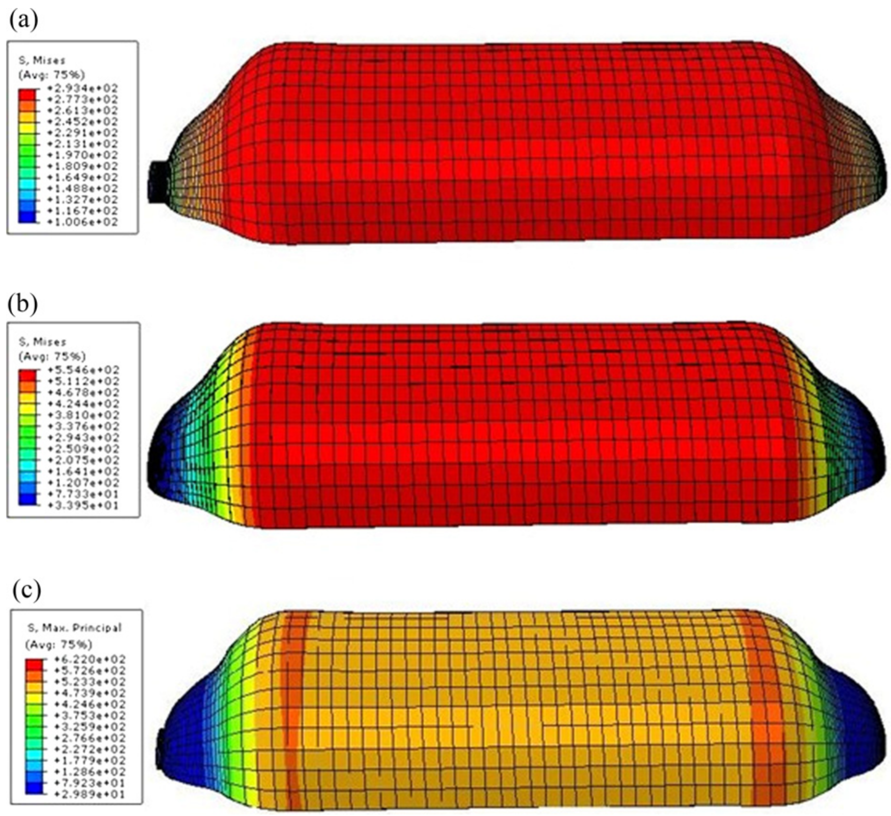


Fig. 6. Schematic stress distributions at (a) liner, (b) hoop wound layer and (c) spiral wound layer for a designed composite vessel.

Nahas [71], Tsai [72] and Sleight [73] performed extensive literature surveys on the failure theories of composites and classified the failure criteria into two types: the non-interactive failure criteria and interactive failure criteria. The non-interactive failure criterion is defined as one without interactions between the stress or strain components. These criteria compare the individual stress or strain components with the corresponding material allowable strengths, and indicate the type of failure modes. The maximum stress, Hashin, Christensen, Rotem, McCartney, Yamada-Sun, Chang-Chang, Puck and Huang's criteria belong to this type. In contrast, the interactive failure criteria consider interactions between stress components. These theories use a polynomial based on the material strengths to describe a failure surface. The Tsai-Wu, Tsai-Hill and Hoffman failure criteria belong to this type. Currently, there is also an evolving trend to develop the fracture energy-based failure criteria to predict the failure of composites using such as the cohesive fracture energy-based criterion [74,75] and finite element failure-based criterion [76,77]. However, accurate prediction of fracture properties of composites requires advanced experimental technique.

4.3. Progressive failure analysis

Essentially, progressive failure analysis of the composite vessel is to implement the proposed damage constitutive model, the failure criteria and damage evolution law. Garnich and Akula [78], Orifici et al. [79], and Liu and Zheng [24] gave reviews on the current methods on the progressive failure analysis and finite element implementation of composites. The finite element equation under the hygro-thermo-mechanics field is given by

$$Ku = F_s + F_T + F_C \tag{15}$$

where $K = \int_V B^T C_d B\, dV$ is the stiffness matrix of a finite element, $F_s = \int_S N^T F_s\, dS$, $F_T = \int_V B^T C_d \alpha\, \Delta T\, dV$ and $F_C = \int_V B^T C_d \beta\, \Delta C\, dV$ are element forces arising from the surface load, thermal expansion and moisture expansion, respectively. $B = LN^T$ is strain matrix, L is differential operator and N is shape function.

The flow chart for the progressive failure analysis of the composite vessel using finite element method is illustrated in Fig. 7, as summarized by five points [73]: (1) for each load step, the finite element analysis is performed and the on-axis stresses/strains at each element are obtained, (2) the stresses/strains at each element are compared with the material allowable values and used to determine whether some elements fail according to the failure criteria. If no failure is detected, the applied load is increased and the analysis continues, (3) if some elements fail, the damage variables are updated, and the element stiffness constants are degraded according to the damage model. After that, the equilibrium of the composite vessel is re-established using the modified stiffness. This adjustment accounts for the nonlinear solution due to the stiffness change, (4) the calculations are performed continuously under the same load until there is no failed element anymore, (5) the iterative process repeats until the catastrophic failure showing the burst of the composite vessel.

Chang [80] and Ju et al. [81] performed the initial and progressive failure analysis of the composite vessel based on the CCLT. However, the analysis is only limited to the analytical solution. Further, Perreux and Thiebaud [82], Liu and Zheng [35] performed the progressive failure analysis of the composite vessel by proposing damage models and developed the corresponding finite element technique. The numerical convergence problem is solved by introducing the arc-length algorithm or viscous stabilization method [83,84]. The fracture localization problem is addressed by adding a characteristic parameter into the damage model to eliminate the mesh effect [85]. However, to develop the

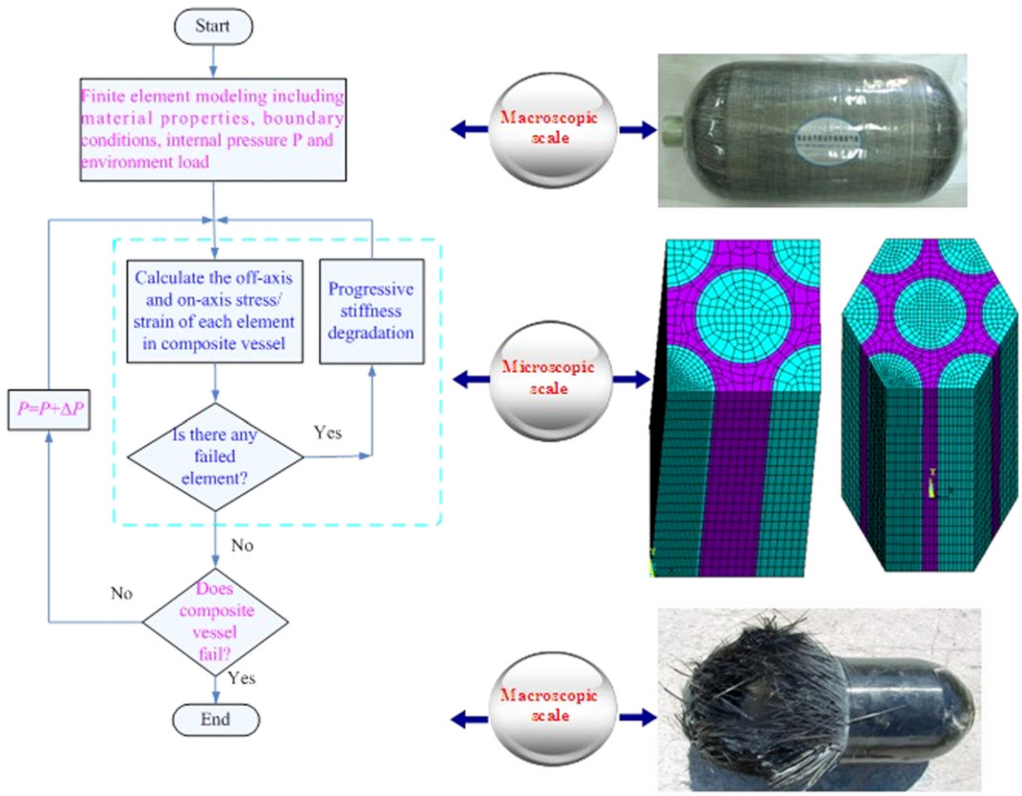


Fig. 7. Flow chart of progressive failure analysis of composite vessel.

finite element technique for the failure analysis under the hygro-thermo-mechanics multiphysics field may still require a long way.

Since the failure of composite is the macroscopic representation of the microscopic fiber/matrix failure evolvement, it is insufficient to explore the failure properties of composite vessels merely by using the CDM theory. In the past two decades, there were continuous efforts for developing hierarchical and multiscale finite element methods to perform the progressive failure analysis of composites. The multiscale damage model at the microscopic and macroscopic scales for the composite vessel is shown in Fig. 7. Square and hexagonal cell models are established at the microscopic scale based on the observation of carbon fiber/epoxy composites using scanning electron microscope. Thus, the macroscopic damage tensors above can be represented by microscopic damage information. He and Wang [86] studied the transverse matrix cracking and stress concentration for the composite vessel by multiscale failure analysis. Haj-Ali and Muliana [87] proposed an integrated micromechanics framework for the nonlinear analysis of composites. However, these work is only limited to the simple composite structures. Further, Blassiau et al. [88] established the microscopic cell models on the fiber/matrix load transfer and the multiscale model on the progressive failure analysis of the composite vessel. However, the failure properties of the microscopic epoxy matrix was not considered and the damage initiation information for the fiber/matrix interface cannot be acquired. With the development of computer, the computational ability for the multiscale analysis linking the microscopic to macroscopic failure analysis is largely improved. Potential difficulty lies how to reveal all microscopic failure mechanisms in a realistic way which may be elusive of engineering tests [74].

4.4. Burst pressure prediction

Burst pressure of the composite vessel is the ultimate aim of progressive failure analysis. Mao et al. [89] estimated the burst pressure based on the statistical approach and experiments. Cohen et al. [90,91] investigated the effects of manufacturing and design variables such as the material parameters and wound parameters on the strength and stiffness of the composite vessel by experiments. Hwang et al. [92,93] performed the probabilistic failure analysis and experimental tests to predict the size effect on the burst pressure of composite vessels using Monte Carlo method. However, no information on the progressive failure properties of composites is obtained from these work. Sun et al. [94] performed the nonlinear finite element analysis to predict the burst pressure of the composite vessel using the maximum stress failure criterion and a stiffness degradation model. Onder et al. [95] explored the influence of temperature and wound angle on the burst pressure of the composite vessel by the modified CCLT and experiments. However, they defined only the constant degradated stiffness regardless of the evolvement of damage variables. Based on the modified CCLT and CDM, Liu and Zheng [35,96] proposed damage models and finite element algorithm, respectively, to predict the burst pressure of the composite vessel by considering the progressive failure properties and nonlinear damage evolvement. Prediction of the burst pressure is essentially related to the numerical convergence problem in the finite element analysis. According to the design requirement of the composite vessel, only little matrix cracking under working pressure is permitted. As the pressure increases, progressive interface debonding and matrix cracking appear. Only when a large number of fiber breakage suddenly appears is the composite vessel considered to burst.

5. Optimal design of composite hydrogen storage vessel

The aim of design for the composite vessel is to reach the best match between the reliability and practicability. Advanced design technique can shorten the duration and save the cost. Now, the ISO (International Standardization Organization) and European Union have issued the standards for the design of composite vessel [97,98]. Unluckily, there is still no mature national standard of composite vessel until now in China since most of the design and manufacturing depend on the experience and experiment [99,19]. In this case, developing a set of efficient design method is necessary. Now, two main design methods for the composite vessel sprout: safety coefficient-based design, and reliability and lifetime-based design, which are considered as the improvement over the conventional experiential design.

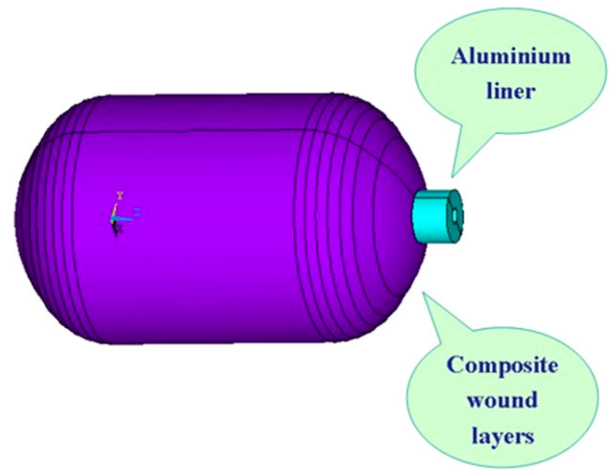


Fig. 8. Optimization model of composite vessel.

5.1. Safety coefficient-based design

According to Leung [100], the working pressure of composite vessel is taken as the burst pressure divided by the safety coefficient. However, the difficulty lies in how to select a proper safety coefficient which yet depends on the design and manufacturing levels. The CGH2R Draft Revision 10 of European Union and the ISO/DIS 15869.2 specify the safety coefficients of 2.35 and 2.25, respectively [97,98]. Then, the optimal design attempts to reach the minimum weight and highest strength under the constraint of safety coefficient. Tummala et al. [101] performed the multiobject optimization of the composite vessel on the pressure, temperature and weight. Krikanov [102] proposed a new optimization method to design the composite vessel with the minimum mass under strain and strength constraints. Especially, Liang et al. [103] carried out the optimal design of dome contours for the composite vessel subjected to geometric limits and wound condition. Wang and Zheng [37] proposed a mathematical design model based on the finite element analysis. However, the optimization efficiency above is low since only simple optimization methods are used. In this case, searching advanced intellectual algorithms becomes necessary. Ghiasi et al. [104] compared the optimization efficiency of various methods such as the gradient-based method, direct search method, genetic algorithm and simulated annealing. Messager et al. [105] developed a genetic algorithm-based optimization method to maximize the stability buckling pressure of the composite vessel. Kim et al. [106] proposed an optimal design method of the composite vessel by associating the finite element analysis with the genetic algorithm. Liu et al. [107,108] proposed an adaptive genetic algorithm and an immune algorithm, respectively, to perform the optimal design of the composite vessel which aims to reach the minimum weight under the constraints of safety coefficient and processing parameters. The parametric model for the composite vessel is shown in Fig. 8. The intellectual optimization algorithms show higher convergence speed and precision than the gradient-based method.

5.2. Reliability and lifetime-based design

For a designed composite vessel, economy and practicability are based on safety and reliability. The reliability and lifetime of the composite vessel relate to many factors such as the material parameters, wound patterns and manufacturing defects. It is not always feasible to expect to use a single safety coefficient to provide the guarantee for any occasional accident. Thus, it is necessary to develop the reliability and lifetime-based methods to perform the probabilistic design. Compared with the deterministic design method, the probabilistic design method may avoid costly overdesign and conservative manufacturing.

Now, the reliability and lifetime-based design conception has been successfully applied to the composite vessel. Béakou et al. [109,110] optimized the wound angle of cylindrical composite laminates using reliability methods for the composite structure. Gomes et al. [111] performed the optimization of laminated composites under the reliability constraint using genetic algorithm and neural network. However, the geometry model in there work is much simpler than the composite vessel. Further, Shen et al. [112] launched the reliability-based probabilistic design of the composite vessel by combining the statistical theory and experiments. However, the probabilistic design is only limited to the analytical solution using the grid theory. Cai et al. [113] developed a set of reliability-based design method of the composite vessel and performed the sensitivity analysis on the influence of statistical variables on the safety factors under external pressure. Based on the progressive failure analysis, Liu and Zheng [114] performed the strength reliability-based design of the composite vessel using Monte Carlo simulation and response surface method, in which the lay-up thickness and angles of composite layers are considered as the stochastic variables. Besides, Wang [115] compared several existing lifetime prediction technique of the composite vessel under static and cyclic internal pressure. Camara et al. [116] studied the strength reliability, the failure probabilities and the lifetime of the composite vessel by multiscale modeling and composite micromechanics. Bie et al. [117] proposed a theoretical model to predict the fatigue lifetime of the composite vessel by combining the micromechanics and CDM. However, the research above did not touch upon the lifetime-based design. Comond et al. [118] proposed a set of fatigue lifetime-based design method of the composite vessel based on the modified CCLT and the CDM. However, the design for the head part was not considered in their work. Further, Bertin et al. [119] explored the effects of wound patterns on the fatigue lifetime of the composite vessel under thermomechanical cyclic loading by experiments. It can be concluded the strength reliability and lifetime-based material-structure-processing integrated design technique will become an important tendency for the design of composite vessel. The best design method is to set up the high-fidelity numerical simulation and advanced optimization platform. But, the design must also consider too many factors including the statistical properties of fiber strengths, complex geometry structure, and efficiency and stability of numerical calculations. For the probabilistic design, the prediction of the burst pressure and fatigue lifetime of composite vessel is main limitation which otherwise needs more fundamental research. After all, the complicated failure mechanisms of composites are still beyond our understanding until now [120].

6. Further prospect of composite hydrogen storage vessel

In recent years, the composite pressure vessels develop rapidly in the field of hydrogen storage. Academic and engineering attentions are paid to the design and manufacturing technique of them. With the development of computer-aided design technique, the composite vessel offers designers much design space. The design is to reach the ideal match among the reliability and lifetime, weight and cost.

It is commonly recognized the composite vessel should take on the lightweight road [121]. The lightweight design, manufacturing, test and evaluation technique guarantee the safe and economical application of composite vessel. The ideal design method is to set up a set of material-structure-processing integrated design platform, and to solve the numerical simulation and optimization problems efficiently. This is not easily realized in view of the complicated relationships between the design requirements and design parameters.

The composite vessel is an important application of such as the advanced carbon fiber/epoxy composites to the area of hydrogen energy. The complicated failure mechanisms and degradation mechanisms are distinct characteristic of composites although they exhibit high stiffness- and strength-density ratios. Further, the hygro-thermo-mechanics environment is also a large problem in the design of the composite vessel. More fundamental research on the failure properties of composites under the multiphysics field remains to be performed.

Acknowledgements

This research is supported by the National Natural Science Funding of China (Number: 50905197), the High-Technology Research and Development Program (863 Key Program) of China (Number: 2009AA044801) and the Key Project of National Programs for Fundamental Research and Development (973 Program) of China (Number: 2007CB209706).

References

[1] Momirlan M, Veziroglu TN. Current status of hydrogen energy. Renewable and Sustainable Energy Reviews 2002;6(1–2):141–79.
[2] Abbasi T, Abbasi SA. 'Renewable' hydrogen: prospects and challenges. Renewable and Sustainable Energy Reviews 2011;15(6):3034–40.
[3] Midilli A, Ay M, Dincer I, Rosen MA. On hydrogen and hydrogen energy strategies. I. Current status and needs. Renewable and Sustainable Energy Reviews 2005;9(3):255–71.
[4] Midilli A, Ay M, Dincer I, Rosen MA. On hydrogen and hydrogen energy strategies. II. Future projections affecting global stability and unrest. Renewable and Sustainable Energy Reviews 2005;9(3):273–87.
[5] Klejin R, Voet EV. Resource constraints in a hydrogen economy based on renewable energy sources: an exploration. Renewable and Sustainable Energy Reviews 2010;14(9):2784–95.
[6] Saxena RC, Seal D, Kumar S, Goyal HB. Thermo-chemical routes for hydrogen rich gas from biomass: a review. Renewable and Sustainable Energy Reviews 2008;12(7):1909–27;
Moharana MK, Peela NR, Khandekar S, Kunzru D. Distributed hydrogen production from ethanol in a microfuel processor: issues and challenges. Renewable and Sustainable Energy Reviews 2011;15(1):524–33.
[7] Sobrino FH, Monroy CR, Pérez JLH. Critical analysis on hydrogen as an alternative to fossil fuels and biofuels for cars in Europe. Renewable and Sustainable Energy Reviews 2010;14(2):772–80.
[8] Rosyid OA, Jablonski D, Hauptmanns U. Risk analysis for the infrastructure of a hydrogen economy. International Journal of Hydrogen Energy 2007;32(15):3194–200.
[9] Zoulias EL, Glockner R, Lymberopoulos N, Tsoutsos T, Vosseler I, Gavalda O, Mydske HJ, Taylor P. Integration of hydrogen energy technologies in stand-alone power systems analysis of the current potential for applications. Renewable and Sustainable Energy Reviews 2006;10(5):432–62.
[10] Mao ZQ. The bridge to future hydrogen economy. Journal of Wuhan University of Technology 2006;28(21):6–10.
[11] Züttel A. Materials for hydrogen storage. Materials Today 2003;6(9):24–33.
[12] Chen P, Zhu M. Recent progress in hydrogen storage. Materials Today 2008;11(12):36–43.
[13] Zhou L. Progress and problems in hydrogen storage methods. Renewable and Sustainable Energy Reviews 2005;9(4):395–408.
[14] Zheng JY, Liu XX, Xu P, Liu PF, Zhao YZ, Yang J. International Journal of Hydrogen Energy 2012;37(1):1048–57.
[15] Xu P, Zheng JY, Liu PF, Chen R, Kai FM, Li L. Risk identification and control of stationary high-pressure hydrogen storage vessels. Journal of Loss Prevention in the Process Industries 2009;22(6):950–3.
[16] Young KS. Advanced composites storage containment for hydrogen. International Journal of Hydrogen Energy 1992;17(7):505–7.
[17] Vasiliev VV, Krikanov AA, Razin AF. New generation of filament-wound composite pressure vessels for commercial applications. Composite Structures 2003;62(3–4):449–59.
[18] Xue ZM. The discussion about variant design formulation for fibre wound internal pressure container with metal lining. Fiber Reinforced Plastics/Composites 1991;4:22–6 [in Chinese].
[19] Zheng JY, Bie HY, Xu P, Liu PF, Chen HG, Huston D. Investigation on standards of fully-wrapped composite tanks for on-board storage of high pressure hydrogen. Pressure Vessel Technology 2007;24(11):48–56 [in Chinese].
[20] Cox BN, Yang QD. In quest of virtual tests for structural composites. Science 2006;314(5802):1102–7.
[21] Kumar S, Curtin WA. Crack interaction with microstructure. Materials Today 2007;10(9):34–44.
[22] Van der Giessen E, Needleman A. Micromechanics simulations of fracture. Annual Review of Materials Research 2002;32:141–62.
[23] Needleman A. Computational modeling of material failure. Applied Mechanics Reviews 1994;47(2):34–42.
[24] Liu PF, Zheng JY. Recent developments on damage modeling and finite element analysis for composite laminates: a review. Materials and Design 2010;31(8):3825–34.
[25] Liu PF, Zheng JY. Review on methodologies of progressive failure analysis of composite laminates. In: Koppel A, Oja J, editors. Continuum mechanics. New York: Nova Science Publishers; 2009 [Chapter 11].
[26] Holland JH. Adaptation in natural and artificial systems. Ann Arbor: University of Michigan Press; 1975.
[27] Kirkpatrick S, Gelatt CD, Vecchi MP. Optimization by simulated annealing. Science 1983;220(4598):671–80.
[28] Medzhitov R. Recognition of microorganisms and activation of the immune response. Nature 2007;449:819–26.
[29] Yang FQ, Zhang TP, Liu ZD, Wang XY. Finite element modeling and buckling analysis of COPV. Vacuum and Cryogenics 2005;11(1):40–5 [in Chinese].
[30] Chen RX. Design analysis on the filament-wound gascylinder. Journal of Solid Rocket Technology 2008;31(6):625–34 [in Chinese].
[31] Lifshitz JM, Dayan H. Filament-wound pressure vessel with thick metal liner. Composite Structures 1995;32(1–4):313–23.
[32] Parnas L, Katirci N. Design of fiber-reinforced composite pressure vessels under various loading conditions. Composite Structures 2002;58(1):83–95.
[33] Chapelle D, Perreux D. Optimal design of a Type 3 hydrogen vessel. Part I. Analytic modeling of the cylindrical section. International Journal of Hydrogen Energy 2006;31(5):627–38.
[34] Yan F, Dai HD, Zhu ZC. Finite element analysis technology of filament wound pressure vessel structure. Aerospace Shanghai 2003;20(6):33–6 [in Chinese].
[35] Liu PF, Zheng JY. Progressive failure analysis of carbon fiber/epoxy composite laminates using continuum damage mechanics. Materials Science and Engineering A 2008;485(1–2):711–7.
[36] Xu P, Zheng JY, Liu PF. Finite element analysis of burst pressure of composite hydrogen storage vessels. Materials and Design 2009;30(7):2295–301.
[37] Wang ZH, Zheng Q. Finite element optimization design of the full-wrapped composite vessel. Journal of Wuhan University of Technology 2009;31(5):733–5 [in Chinese].
[38] Li P, Sheng ZH, Wu YC. Parametric structure analysis of full-wrapped composite cylinder based on ANSYS. Mechanical Research and Application 2007;20(2):114–6 [in Chinese].
[39] Antunes PJ, Dias GR, Nunes JP, Van Hattum FWJ, Oliveira T. Finite element modeling of thermoplastic matrix composite gas cylinders. Journal of Thermoplastic Composite Materials 2008;21(5):411–41.
[40] Park JS, Hong CS, Kim CG, Kim CU. Analysis of filament wound composite structures considering the change of wound angles through the thickness direction. Composite Structures 2002;55(1):63–71.
[41] Kim CU, Hong JH, Hong CS, Kim CG. Optimal design of filament wound structures under internal pressure based on the semi-geodesic path algorithm. Composite Structures 2005;67(4):443–52.
[42] Zheng CX. Composite pressure vessel. University of Chemical Engineering Press: Biejing; 2006.
[43] Kachanov LM. Time of the rupture process under creep conditions. Izvestiya Akademii Nauk SSSR, Otdelenie Teckhnicheskikh Nauk 1958;8:26–31.
[44] Spottswood SM, Palazotto AN. Progressive failure analysis of a composite shell. Composite Structures 2007;53(1):117–31.
[45] Phillips EA, Herakovich CT, Graham LL. Damage development in composites with large stress gradients. Composites Science and Technology 2001;61(15):2169–82.
[46] Maimí P, Camanho PP, Mayugo JA, Dávila CG. A continuum damage model for composite laminates. Part I. Constitutive model. Mechanics of Materials 2007;39(10):897–908.

[47] Maimí P, Camanho PP, Mayugo JA, Dávila CG. A continuum damage model for composite laminates. Part II. Computational implementation and validation. Mechanics of Materials 2007;39(10):909–19.
[48] Maa RH, Cheng JH. A CDM-based failure model for predicting strength of notched composite laminates. Composites B: Engineering 2002;33(6):479–89.
[49] Camanho PP, Maimí P, Dávila CG. Prediction of size effects in notched laminates using continuum damage mechanics. Composites Science and Technology 2007;67(13):2715–27.
[50] Barbero EJ, Vivo LD. A constitutive model for elastic damage in fiber-reinforced PMC Laminae. International Journal of Damage Mechanics 2001;10(1):73–93.
[51] Lemaitre J, Chaboche JL. Mechanics of solid materials. Cambridge: Cambridge University Press; 1990.
[52] Lemaitre J. A course on damage mechanics. Berlin: Springer-Verlag; 1992.
[53] Ristinmaa M, Ottosen NS. Viscoplasticity based on an additive split of the conjugated forces. European Journal of Mechanics A: Solids 1998;17(2): 207–35.
[54] Schapery RA. A theory of mechanical behavior of elastic media with growing damage and other changes in structure. Journal of Mechanics and Physics of Solids 1990;38(2):215–53.
[55] Murakami S, Kamiya K. Constitutive and damage evolution equations of elastic–brittle materials based on irreversible thermodynamics. International Journal of Mechanical Science 1997;39(4):473–86.
[56] Hayakawa K, Murakami S, Liu Y. An irreversible thermodynamics theory for elastic–plastic-damage materials. European Journal of Mechanics A: Solids 1998;17(1):13–32.
[57] Simo JC, Ju JW. Strain- and stress-based continuum damage models. International Journal of Solids and Structures 1987;23(7):821–40.
[58] Tsai SW, Wu EM. A general theory of strength for anisotropic materials. Journal of Composite Materials 1971;5(1):58–80.
[59] Hoffman O. The brittle strength of orthotropic material. Journal of Composite Materials 1967;1(2):200–6.
[60] Hinton MJ, Soden PD. Predicting failure in composite laminates: the background to the exercise. Composites Science and Technology 1998;58(7):1001–10.
[61] Soden PD, Hinton MJ, Kaddour AS. A comparison of the predictive capabilities of current failure theories for composite laminates. Composites Science and Technology 1998;58(7):1225–54.
[62] Theocaris PS. Weighing failure tensor polynomial criteria for composites. International Journal of Damage Mechanics 1992;1(1):4–46.
[63] Rotem A, Hashin Z. Failure modes of angle ply laminates. Journal of Composite Materials 1975;9(2):191–206.
[64] Narayanaswami R, Adelman HM. Evaluation of the tensor polynomial and hoffman strength theories for composite materials. Journal of Composite Materials 1977;11(4):366–77.
[65] Hashin Z. Failure criteria for unidirectional fiber composites. Journal of Applied Mechanics 1980;47(2):329–34.
[66] Yamada SE, Sun CT. Analysis of laminated strength and its distribution. Journal of Composite Materials 1978;12(3):275–84.
[67] Christensen RM. Tensor transformations and failure criteria for the analysis of fiber composite materials. Journal of Composite Materials 1988;22(9):874–97.
[68] Chang FK, Chang KY. A progressive damage model for laminated composites containing stress concentrations. Journal of Composite Materials 1987;21(9):834–55.
[69] Puck A, Schürmann H. Failure analysis of FRP laminates by means of physically based phenomenological models. Composites Science and Technology 1998;58(7):1045–67.
[70] Huang ZM. Failure analysis of laminated structures by FEM based on nonlinear constitutive relationship. Composite Structures 2007;77(3):270–9.
[71] Nahas MN. Survey of failure and post-failure theories of laminated fiber-reinforced composites. Journal of Composites Technology and Research 1986;8(4):138–53.
[72] Tsai SW. A survey of macroscopic failure criteria for composite materials. Journal of Reinforced Plastics and Composites 1984;3(1):40–62.
[73] Sleight DW. Progressive failure analysis methodology for laminated composite structures. NASA Report 1999;4:8–63.
[74] Cox B, Yang QD. Cohesive models for damage evolution in laminated composites. International Journal of Fracture 2005;133(2):107–37.
[75] Rami HA. Cohesive micromechanics: a new approach for progressive damage modeling in laminated composites. International Journal of Damage Mechanics 2009;18(8):691–719.
[76] Tay TE, Tan SHN, Tan VBC, Gosse JH. Damage progression by the element-failure method (EFM) and strain invariant failure theory (SIFT). Composites Science and Technology 2005;65(6):935–44.
[77] Tay TE, Liu G, Tan VBC, Sun XS, Pham DC. Progressive failure analysis of composites. Journal of Composite Materials 2008;42(18):1921–66.
[78] Garnich MR, Akula VMK. Review of degradation models for progressive failure analysis of fiber reinforced polymer composites. Applied Mechanics Reviews 2009;62(1):1–33.
[79] Orifici AC, Herszberg I, Thomson RS. Review of methodologies for composite material modeling incorporating failure. Composite Structures 2008;86(1–3):194–210.
[80] Chang RR. Experimental and theoretical analyses of first-ply failure of laminated composite pressure vessels. Composite Structures 2000;49(2):237–43.
[81] Ju JH, Pickle BD, Morgan RJ, Reddy JN. An initial and progressive failure analysis for cryogenic composite fuel tank design. Journal of Composite Materials 2008;42(6):569–92.
[82] Perreux D, Thiebaud F. Damaged elasto-plastic behaviour of [$+\varphi,-\varphi$] fibre-reinforced composite laminates in biaxial loading. Composites Science and Technology 1995;54(3):275–85.
[83] Crisfield MA. An arc-length method including line searches and accelerations. Internatioal Journal of Numerical Methods in Engineering 1983;19(9):1269–89.
[84] Duvaut G, Lions JL. Inequalities in mechanics and physics. Berlin: Springer; 1976.
[85] Lapczyk I, Hurtado JA. Progressive damage modeling in fiber-reinforced materials. Composites A: Applied Science and Manufacturing 2007;38(11):2333–41.
[86] He PF, Wang HW. Micro-mechanics research the strength of filament-wound pressure vessels. Fiber Reinforced Plastics/Composites 1999;(4):22–6 [in Chinese].
[87] Haj-Ali RM, Muliana AH. A multi-scale constitutive formulation for the nonlinear viscoelastic analysis of laminated composite materials and structures. International Journal of Solids and Structures 2004;41(13):3461–90.
[88] Blassiau S, Thionnet A, Bunsell AR. Micromechanisms of load transfer in a unidirectional carbon fibre-reinforced epoxy composite due to fibre failures. Part 3. Multiscale reconstruction of composite behavior. Composite Structures 2008;83(3):312–23.
[89] Mao CS, Yang MF, Hwang DG, Wang HC. An estimation of strength for composite pressure vessels. Composite Structures 1992;22(3):179–86.
[90] Cohen D, Mantell SC, Zhao LY. The effect of fiber volume fraction on filament wound composite pressure vessel strength. Composites B: Engineering 2001;32(5):413–29.
[91] Cohen D. Influence of filament wound parameters on composite vessel quality and strength. Composites A: Applied Science and Manufacturing 1997;28(12):1035–47.
[92] Hwang TK, Hong CS, Kim CG. Probabilistic deformation and strength prediction for a filament wound pressure vessel. Composites B: Engineering 2003;34(5):481–97.
[93] Hwang TK, Hong CS, Kim CG. Size effect on the fiber strength of composite pressure vessels. Composite Structures 2003;59(4):489–98.
[94] Sun XK, Du SY, Wang GD. Bursting problem of filament wound composite pressure vessels. International Journal of Pressure Vessels and Piping 1999;76(1):55–9.
[95] Onder A, Sayman O, Dogan T, Tarakcioglu N. Burst failure load of composite pressure vessels. Composite Structures 2009;89(1):159–66.
[96] Zheng JY, Liu PF. Elasto-plastic stress analysis and burst strength evaluation of Al-carbon fiber/epoxy composite cylindrical laminates. Computational Materials Science 2008;42(3):453–61.
[97] ISO/DIS 15869.2. Gaseous hydrogen and hydrogen blend land vehicle fuel tanks.
[98] CGH2R draft revision 10. Hydrogen vehicles: on-board. Storage systems draft ECE compressed gaseous hydrogen regulation revision 10.
[99] Zheng JY, Fu Q, Kai FM, Chen CP. The state of art of lightweight high pressure hydrogen storage tanks. Acta Energiae Solaris Sinica 2004;25(5):576–81 [in Chinese].
[100] Leung JC. A theory on the discharge coefficient for safety relief valve. Journal of Loss Prevention in the Process Industries 2004;17(4):301–13.
[101] Tummala M, Krepec T, Ahmed AKW. Optimization of thermocontrolled tank for hydrogen storage in cars. International Journal of Hydrogen Energy 1997;22(5):525–30.
[102] Krikanov AA. Composite pressure vessels with higher stiffness. Composite Structures 2000;48(1–3):119–27.
[103] Liang CC, Chen HW, Wang CH. Optimum design of dome contour for filament-wound composite pressure vessels based on a shape factor. Composite Structures 2002;58(4):469–82.
[104] Ghiasi H, Pasini D, Lessard L. Optimum stacking sequence design of composite materials. Part I. Constant stiffness design. Composite Structures 2009;90(1):1–11.
[105] Messager T, Pyrz M, Gineste B, Chauchot P. Optimal laminations of thin underwater composite cylindrical vessels. Composite Structures 2002;58(4):529–37.
[106] Kim CU, Hong CS, Kim CG, Kim JY. Optimal design of filament wound type 3 tanks under internal pressure using a modified genetic algorithm. Composite Structures 2005;71(1):16–25.
[107] Liu PF, Xu P, Zheng JY. Artificial immune system for optimal design of composite hydrogen storage vessel. Computational Materials Science 2009;47(1):261–7.
[108] Xu P, Zheng JY, Chen HG, Liu PF. Optimal design of high pressure hydrogen storage vessel using an adaptive genetic algorithm. International Journal of Hydrogen Energy 2010;35(7):2840–6.
[109] Boyer C, Béakou A, Lemaire M. Design of a composite structure to achieve a specified reliability level. Reliability Engineering and System Safety 1997;56(3):273–83.
[110] Béakou A, Mohamed A. Influence of variable scattering on the optimum wound angle of cylindrical laminated composites. Composite Structures 2001;53(3):287–93.
[111] Gomes HM, Awruch AM, Lopes PAM. Reliability based optimization of laminated composite structures using genetic algorithms and artificial neural networks. Structural Safety 2011;33(3):186–95.

[112] Shen J, Xie HQ, Hou DY. Reliability design of fiber wound reinforced plastic pressure vessel. Acta Materiae Compositae Sinica 2006;23(4):124–8 [in Chinese].
[113] Cai BP, Liu YH, Liu ZK, Tian XJ, Ji RJ, Li H. Reliability-based load and resistance factor design of composite pressure vessel under external hydrostatic pressure. Composite Structures 2011;93(11):2844–52.
[114] Liu PF, Zheng JY. Strength reliability analysis of aluminium–carbon fiber/epoxy composite laminates. Journal of Loss Prevention in the Process Industries 2010;23(3):421–7.
[115] Wang XY. Life analysis technique for filament wound pressure cylinders with metal liners used in space system. Fiber Reinforced Plastics/Composites 2007;(5):47–52 [in Chinese].
[116] Camara S, Bunsell AR, Thionnet A, Allen DH. Determination of lifetime probabilities of carbon fibre composite plates and pressure vessels for hydrogen storage. International Journal of Hydrogen Energy 2011;36(10):6031–8.
[117] Bie HY, Li X, Liu PF, Liu YL, Xu P. Fatigue life evaluation of high pressure hydrogen storage vessel. International Journal of Hydrogen Energy 2010;35(7):2633–6.
[118] Comond O, Perreux D, Thiebaud F, Weber M. Methodology to improve the lifetime of type III HP tank with a steel liner. International Journal of Hydrogen Energy 2009;34(7):3077–90.
[119] Bertin M, Touchard F, Lafarie-Frenot MC. Experimental study of the stacking sequence effect on polymer/composite multi-layers submitted to thermomechanical cyclic loadings. International Journal of Hydrogen Energy 2010;35(20):11397–404.
[120] Liu PF, Chu JK, Liu YL, Zheng JY. A study on the failure mechanisms of carbon fiber/epoxy composite laminates using acoustic emission. Materials and Design; in press.
[121] Wang RG, Jiao WC, Liu WB, Yang F, He XD. Research progress of lightweight composite pressure vessel. Aeronautical Manufacturing Technology 2009;(15):86–9 [in Chinese].